Safeswim – Live Information System for Water Quality and Swimming Conditions at Bathing Beaches

B Tuckey[1], N Brown[2], M Neale[3] and K Chakravarthy[1]
[1] DHI Water and Environment, Auckland, New Zealand.
email: bjt@dhigroup.com
[2] Auckland Council, Auckland, New Zealand.
[3] Puhoi Stour, Auckland, New Zealand.

Abstract
Safeswim provides real-time predictions and forecasts of water quality, and up-to-the-minute advice on swimming conditions at over 100 sites around the Auckland region.

This paper focuses on public health risk from contact with recreational waters, and how Safeswim was developed to manage this risk, based on the current New Zealand national guidelines for contact recreation. Auckland, like many global cities, has issues with an aging stormwater and wastewater network, which can result in contamination of its waterways, especially during or after significant rainfall. The limitations of the traditional type of monitoring programmes created the motivation to move to a modelling based approach.

There are two types of approaches (both implemented in Safeswim) used for forecasting water quality:

- a regression type model ('black box'); or
- a process-based type model, which predicts the contaminant concentrations discharged to the receiving environment; and the movement and level of dilution and inactivation that occurs within the receiving environment ('white box' model).

Details are provided of the operational white box forecast model developed by DHI for some beaches in the Waitematā Harbour, Auckland. This includes an overview of both the development of contaminant load models for the wastewater network, and the receiving environment model. The accuracy of the white box model is presented in comparison to the water quality data collected over ten rainfall events, at selected beaches within the model domain. The various methods for dissemination of the information to the public is also presented.

Keywords: Early warning, water forecast, recreational waters, bathing waters, water quality, operational modelling

1. Introduction

Auckland Council is currently developing the Resilient Communities, Catchments and Coastlines (RC^3) programme, which aims to create a sustainable and resilient Auckland.

Auckland is experiencing unprecedented growth, with most of Auckland's development occurring in existing areas. Council organisations, infrastructure providers and private developers are making decisions to invest in developing land and infrastructure that may be significantly impacted by the effects of climate change and sea level rise. There is an urgent need to ensure that policy, regulation, development, and asset management decisions at all levels are cognisant of these risks.

Auckland already has a major infrastructure challenge due to an aging stormwater and wastewater network, which can result in significant contamination to its waterways after storm events. Even small amounts of rainfall (< 5 mm) can result in wet-weather wastewater overflows discharging to streams and ocean receiving environment. Dry weather overflows can also occur in any wastewater network e.g. from pump station failure.

Auckland aspires to have clean beaches and bathing water. However faecal contamination can pose a health risk to bathers [1] [2].

Issues with traditional monitoring for informing the public of bathing health risk created an appetite within council to develop a modelling based forecast approach, which is presented through the Safeswim website [3]. Safeswim provides live information on water quality and swimming conditions (see Figure 1).

Safeswim is also seen as a platform from which Auckland community can work together to take ownership of the decisions and actions that need to be taken to build a more resilient Auckland.

A good example of this in action is the Water Quality Targeted Rate implemented by Auckland Council, to accelerate the water quality improvement programme. A growing awareness of the water quality issues in Auckland's waterways and harbours, resulted in a majority favouring the targeted rate during public engagement.

2. New Zealand Guidelines for Bathing Water Health Risk

In New Zealand, for marine water the preferred indicator for health risk from contact recreation is Enterococci. The Ministry for Environment New Zealand has developed guideline levels of concentrations of Enterococci, to provide an indication of human health risk [4].

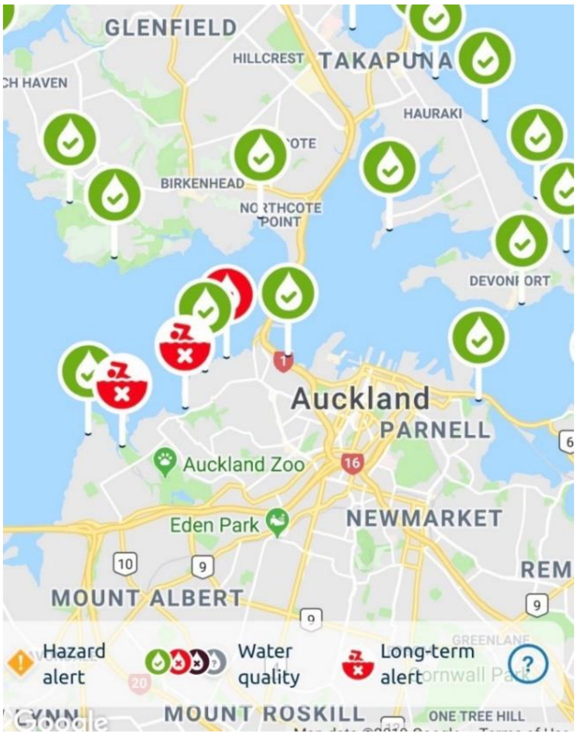

Figure 1 Safeswim web page with nowcast predictions.

Defining the actual risk to public health indicated by a particular count of Enterococci is not possible. This is primarily because the bacteria are an indicator pathogen and not a direct measure of disease causing organisms [4].

A concentration of 280 counts / 100 ml has been incorporated as the critical trigger level for an alert on Safeswim. This value is selected since it is based on keeping illness risks (gastrointestinal and respiratory) associated with recreational water use to less than about 2% [5]. It also corresponds to the level, which when exceeded twice in consecutive samples, triggers "Action mode" level of response, where public should be notified of the health risks for coming in contact with water. In addition, the site is to be considered unsuitable for contact recreation. The 2% risk is derived from epidemiological studies focusing on direct measurement of health effects.

3. Issues with Traditional Monitoring

Traditional recreational monitoring programmes are undertaken through laboratory analysis of water samples. This approach is limited by the highly variable nature of bacteria concentrations in the environment (both temporally and spatially) and the time required for samples to be collected and analysed before results are accessible. There may also be an inherent bias to collect data during fair weather conditions due to health and safety concerns, especially in Auckland where samples were previously collected via helicopter for a significant number of beaches.

In Auckland, samples have traditionally been collected on a weekly basis over the bathing season (typically 1st November to 1st April). Even the most intensive sampling programme does not provide the ability to forecast future conditions due to the requirement to collect and analyse the samples. Also collecting samples only over the bathing season, provides no information outside this period, when recreational use still occurs at many Auckland beaches.

Recent work by Puhoi Stour (unpublished data), further illustrated the short comings of traditional methods. Sampling had been undertaken at Red Beach, Auckland 1995 – 2017 and over this period only one sample of 330 counts / 100 ml exceeded the guidelines. However, when targeted sampling was undertaken for the beach and adjacent stream, for two events, the following was observed:

- 8th November 2017, after 6 mm rain.
  - 4 of 9 samples exceeded guidelines.
  - Stream sample = 17,000 counts / 100 ml.
- 18th January 2018, after 12 mm rain.
  - 7 of 9 samples exceeded guidelines.
  - Stream sample = 5,000 counts / 100 ml.

The targeted sampling illustrated that the health risk for swimming at Red Beach was vastly understated using the traditional monitoring methods.

4. Danish Case Study

Water quality forecasts for bathing health risk have been operational in Denmark and Sweden for over a decade [5]. Similar to Auckland, the objective of these forecast systems has been to provide the public with more detailed information than what can be provided by traditional monitoring, so that public can make informed decisions about health risk.

In August 2010, a triathlon sports competition was held in Copenhagen, Denmark, shortly after an extreme rainfall event. This was despite predictions of poor water quality from the Danish Bathing Water Forecast.

The competition questionnaire was completed by 838 participants (response rate 57%). A total of 351 (42%) respondents confirmed symptoms of diarrhoea or vomiting [6]. This example shows the relevance of a water quality forecast if properly utilised.

5. Types of Forecast Models

Globally there are two types of approaches for forecasting water quality - a data driven regression type model ('a 'black box' model) or a process based type/mechanistic model that predicts the amount of contaminants discharged to the receiving environment and the ultimate fate of the contaminant plume based on the dynamics of the plume and the level of dilution and inactivation that occurs within the receiving environment (a 'white box' model) [7]. The models can provide two types of predictions:

- A predicted 'nowcast' of the current beach water quality based on the most recent observed data.
- A 'forecast' of future beach water quality based on forecasted data.

The white box modelling approach has several advantages over the black box approach, including the ability to provide continuous forecasts in space and time, and the ability to test the effects of management interventions (e.g. infrastructure upgrades) on beach water quality.

Through Safeswim, water quality is now predicted for 107 beaches within the Auckland Region. The majority of these are through a black box model forecast, with eight (within central Waitematā Harbour) from DHI's white box model forecast. The rest of this paper only focuses on white box modelling.

6. White Box Model Forecasting System Set Up

6.1 Data

Forecast spatial rain and wind data are provided by Weather Radar (before April 2019, rain data was provided by MetService). Every six hours, a 72 hour forecast is provided, while a two hour nowcast based on rain radar is continuously updated and provided [8]. Observed rainfall from rain gauges in the Auckland region is provided by Auckland Council.

6.2 Receiving Environment Model

The bathing water forecast system for the central Waitematā Harbour is underpinned by a high-resolution three-dimensional hydrodynamic model, MIKE 3 FM [9], which simulates tidal and wind driven currents within the harbour. The model extent shown in Figure 2, includes the whole Hauraki Gulf, with increased resolution for Waitematā Harbour.

The hydrodynamic model has been calibrated against water level and current data from various locations within the harbour.

During a rainfall event, calculated loads of Enterococci (see Section 6.3) are discharged to the hydrodynamic model and the resulting transport, dilution, and inactivation of the Enterococci plume are simulated as a tracer.

Within the Waitematā Harbour, the main sources of pollutants to the harbour are combined wastewater and stormwater outfalls as well as freshwater inflows. The model does not account for pollutants associated with dry weather overflows or re-suspension of bacteria laden sediments. It is worth noting that simulating suspension of bacteria laden sediments is currently being investigated for the Swedish Bathing Water Forecast [10].

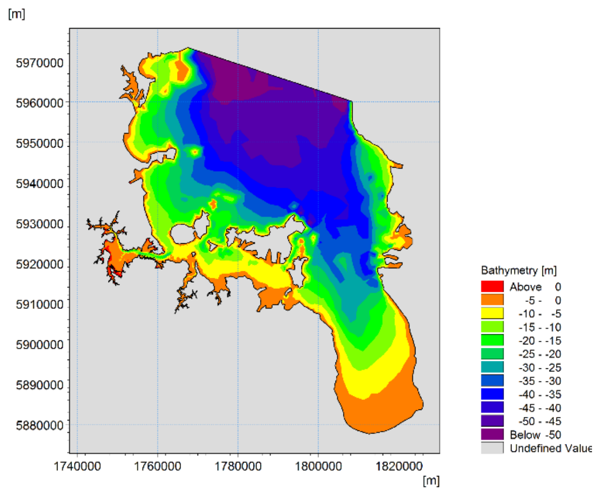

Figure 2 Bathymetry and extent of Hauraki Gulf model.

To account for the decay of Enterococci because of solar radiation, salinity and other processes, a conservative inactivation rate is applied to the tracer in line with recent findings that calculate a first order decay rate constant of Enterococci of between 1 – 2 d^{-1} under low light conditions [11], however it was shown to produce good performance for the model validation (see Section 7).

In parallel, a dynamic water quality model was developed by coupling MIKE ECO Lab [12] with the MIKE 3 FM model. The aim was to represent the inactivation of bacteria in a more sophisticated method, by calculating a varying inactivation rate based on parameters such as water temperature, salinity and light influx. However, this was not implemented as it did not perform significantly better than the constant inactivation rate model and resulted in slower model run times. Simulation run times are a key consideration for operational models.

6.3 Contaminant Load Models

The most up to date network model of the central Auckland network (developed by Watercare) was run for the period 2000 to 2005. Time series of discharge rate for overflows and the associated Enterococci concentration from these simulations were provided to DHI. These were used to derive inputs to the water quality forecast model, by developing relationships for rainfall – overflow and overflow – Enterococci for all overflows within the area of interest.

Where appropriate, overflows from the model were consolidated, however if the overflows were to one of the beaches for which water quality is predicted (e.g. two overflows to St Marys Bay), these remained separate overflows. The overflows within the central Waitematā Harbour model are presented in Figure 3.

Figure 3 Overflows included in central Waitematā Harbour model.

The network model was not calibrated for the eastern beaches covered by the forecast (i.e. Okahu Bay, Mission Bay, Kohimarama Beach and St Heliers Beach). Relationships for the overflows to these beaches were developed from the Integrated Catchment Study (ICS). In 2005, significant contaminant loads to parts of Waitematā and Manukau Harbours from overflows and stormwater, were assessed as part of ICS [13].

The ICS study generated one-year time series of overflow for the consolidated overflows. For the eastern beach overflows, overflow – rainfall relationships were generated based on the ICS time series outputs.

6.4 Operational Platform

MIKE OPERATIONS is the platform which operates the central Waitematā Harbour bathing water quality forecast. The operational system is located on the cloud. This cloud-based system provides greater security and future proofing around service provision (e.g. hardware upgrades and failures, system expansion and minimizing downtime).

A 72-hour forecast, is undertaken every six hours using the latest Weather Radar three day forecasts of rain and wind.

Every hour, a four-hour nowcast is undertaken (-2 hours to +2 hours). This provides two advantages:

1. It ensures real data is used to generate boundary conditions for next 72 hour forecast. This is of key importance to ensure that the forecast captures significant rain events (and the resulting discharge of pollutant to the harbour) that may not have been forecast and alternately, significant rainfall events (and associated discharges) that were forecast, but did not occur, are not included in next forecast.
2. It ensures a more accurate current prediction ('nowcast') of water quality at the beaches.

Before April 2019, for every six hours, a six-hour nowcast (-6 hours to 0 hours) was undertaken to provide initial conditions for forecast. This provided advantage of 1 above but not 2. Hence, the updated white box model with a four-hour nowcast is seen as a significant improvement.

The predicted Enterococci results from the surface of the harbour model are then uploaded to Mott McDonald's Moata (cloud-based analytics and visualisation service) for post-processing, with the nowcast and forecast predictions merged together. These results are then published on the Safeswim website.

If at any time a routine fails within MIKE OPERATIONS, an email alert is sent to DHI and the problem is investigated.

7. Water Quality Model Validation

A comprehensive sampling campaign was undertaken for 10 rainfall events for the eight beaches included within the central Waitematā Harbour white box water quality forecast model. The 10 events occurred in the period, 8th March to 13th July 2017, and covered a range of rainfall intensities, from light to heavy rainfall. Figure 4 presents the predicted contaminant plume for the central Waitematā Harbour, immediately after the 8th March 2017 event.

The sampling campaign required travelling from east to west, visiting the eight beaches on three occasions for each event. Sampling at a beach scale consisted of three sampling locations covering the beach area. Three replicates were collected for each sample. In this way, there were nine samples for each beach, for three occasions over the event sampled (i.e. a total of 27 samples per beach and a total of 216 samples per event).

To assess the performance of the nowcast water quality model (i.e. water quality predictions based on observed rainfall), the observed data was compiled in the following way. Mean Enterococci concentration was determined for all samples collected at each beach based on whether sample was collected in morning or afternoon.

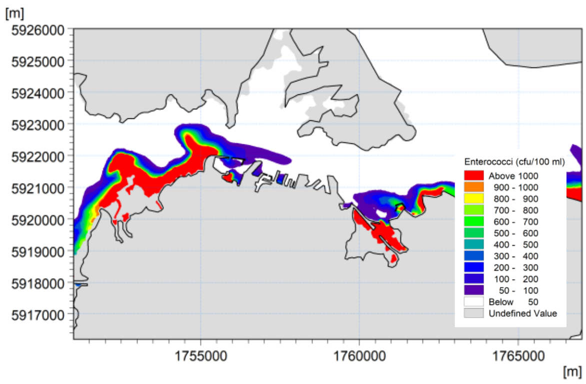

Figure 4 Predicted contaminant plume central Waitematā Harbour.

The predicted mean Enterococci concentrations from the nowcast model were then calculated across three sampling locations at each beach for morning or afternoon.

For both the observed and predicted data, the concentration was determined to be greater or less than the red alert trigger of 280 counts / 100 ml.

A summary of the performance of the model is presented in Table 1 and Table 2, with the following calculated:

1. Accurate - percentage of samples, model accurately predicts no alert or red alert;
2. Accurate or precautionary - percentage of samples that model accurately predicts red alert or predicts a red alert when no alert observed;
3. False negative – percentage of samples, model predicts no alert when red alert is observed; and
4. False positive – percentage of samples, model predicts a red alert when no alert is observed;
5. Sensitivity (exceedances) – percentage of samples that model accurately predicts red alert;
6. Specificity (compliances) – percentage of samples that model accurately predicts no alert.

Ideally, the forecast model should be conservative, minimising instances of false negatives (i.e. no alert predicted when measurements indicate a red alert). Some false positives (i.e. red alert mode predicted when measurements indicate no alert) can be considered acceptable.

All beaches were accurate or precautionary at least 80% of the time. Locations where the Enterococci load models were developed with the most up to date network model were accurate or precautionary at least 90% of the time, with 100% of the time achieved for four out of the five beaches.

It is assumed that if the network model were to be calibrated for the eastern beaches (Mission Bay, Kohimaramara and St Heliers Bay), the nowcast model would also perform better for these locations.

It was concluded that the model was fit for purpose and provided predictions in line with what is recommended by recent publications [14] [15].

Table 1 Summary of nowcast water quality model performance.

Beach	Accurate	Accurate or precautionary	False Negative	False Positive
Pt Chevalier	85%	90%	10%	5%
Herne Bay	80%	100%	0%	20%
Home Bay	90%	100%	0%	10%
St Marys Bay	75%	100%	0%	25%
Okahu Bay	75%	100%	0%	25%
Mission Bay	80%	80%	20%	0%
Kohimarama	95%	95%	5%	0%
St Heliers Bay	80%	85%	15%	5%

Table 2 Summary of nowcast water quality model performance continued.

Beach	Sensitivity (exceedances)	Specificity (compliances)
Pt Chevalier	82%	89%
Herne Bay	100%	56%
Home Bay	100%	75%
St Marys Bay	100%	58%
Okahu Bay	100%	58%
Mission Bay	64%	100%
Kohimarama	90%	100%
St Heliers Bay	75%	88%

As a test of the performance of operational forecast, daily sampling was undertaken over 17 days between 23rd January and 16th February 2018, at Mission Bay; Okahu Bay; and St Heliers. These are the locations where contaminant load model could be improved. Table 3 presents a summary of forecast water quality model performance.

All beaches were accurate at least 71% of the time and accurate or precautionary at least 82% of the time.

This further supports that the model was fit for purpose and provided predictions in line with what is recommended by recent publications [14] [15].

Table 3 Summary of forecast water quality model performance.

Beach	Mission Bay	Okahu Bay	St Heliers Bay
Accurate	88%	71%	71%
Accurate or precautionary	94%	82%	94%
False negative	6%	18%	6%
Sensitivity	80%	67%	83%

8. Dissemination of Information to the Public

Results from both the black box and white box type forecast models are presented on Safeswim (web page developed by Translate Digital). Figure 1 shows the Safeswim web page with nowcast predictions. A green icon, indicates a low risk of contact with water that fails national water quality guidelines for swimming. A red icon indicates a high risk of contact with water that fails national water quality guidelines for swimming.

Navigating to a specific beach will provide a three day forecast of water quality at the beach, broken down into two hour windows. Other information such as wind, tide and rain forecast are also provided for the corresponding period (see Figure 5).

Beach details can also be obtained such as facilities at the beach along with Surf Lifesaving patrol hours (if the beach patrolled). Surf Lifesaving and Public Health officers also have the ability to override the water quality prediction alert with a hazard alert (i.e. stinging jellyfish, sharks or toxic sea slugs). Beaches with permanent no swim warnings are indicated with long-term alerts.

Some wastewater overflows have flow or level sensors installed and if these sensors are triggered, the water quality prediction is overridden by a different alert. A black alert icon is presented, which indicates a very high risk of coming into contact with water that fails national water quality guidelines for swimming.

At selected beaches, digital signs are also being trialled, which display the beach specific data displayed on Safeswim webpage (see Figure 6). These help to inform public of any health risk of swimming at that beach and raise public awareness of the Safeswim concept.

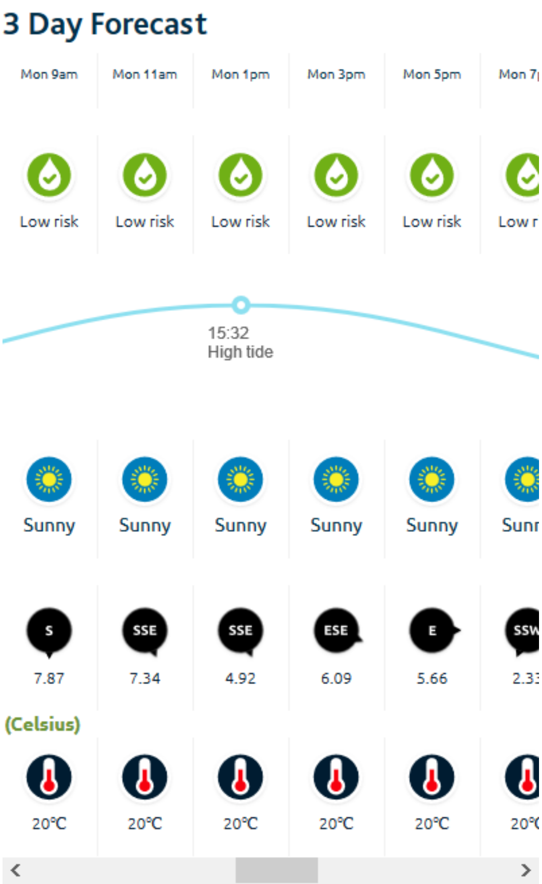

Figure 5 Safeswim web page with nowcast predictions.

Figure 6 Digital sign at Takapuna Beach.

9. Summary

Auckland has an infrastructure challenge due to an aging stormwater and wastewater network, which can result in significant contamination to its waterways after rainfall.

Issues with traditional monitoring for informing the public of bathing health risk were the genesis of the development of a modelling based forecast approach, Safeswim. Safeswim provides live information on water quality and swimming conditions.

Safeswim has two types of water quality forecast models - a black box model, otherwise known as a regression model or a white box model, otherwise known as a mechanistic or process-based model.

DHI developed a white box model for eight beaches in central Waitematā Harbour. This was underpinned by a calibrated three-dimensional hydrodynamic model of the receiving environment and contaminant load models for combined overflows to harbour. The water quality model was validated against extensive sampling. The white box model provides both nowcasts and 72-hour forecasts of water quality at these beaches.

Any major infrastructure work to the Auckland network must now typically illustrate the benefits with regards to Safeswim outcomes as part of the project's cost benefit analysis. The white box model can be run offline to facilitate this process.

10. Acknowledgements

Safeswim is a joint initiative between Auckland Council, Watercare, Surf Lifesaving Northern Region and the Auckland Regional Public Health Service.

Along with these organisations, DHI Water and Environment, Puhoi Stour, Mott McDonald and Translate Digital have all played key roles in the design, development and implementation of Safeswim.

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